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HIGH-RESOLUTION MONITORING AT PARKFIELD

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ABSTRACT

The primary role of the borehole network project is to complement surface networks by adding 3-component waveform coverage of very low amplitude seismic signals typically associated with very low magnitude seismicity and nonvolcanic tremor. These data are primarily used for fundamental research on fault zone and earthquake processes and to provide information for phase determinations for earthquake locations. The high sensitivity to low amplitude signals has also led to the discovery of nonvolcanic tremors on the San Andreas Fault in 2004, and continued operation of the borehole stations allows for continued monitoring and research of these (and possibly other yet undiscovered) phenomena. Over time, data from this project has spawned a variety of research efforts resulting in numerous publications on seismicity-inferred high-resolution fault structure, fault zone guided waves, earthquake recurrence and scaling, mapping of deep fault creep from microearthquake recurrence, and most recently the discovery of non-volcanic tremor in the Cholame region south of Parkfield, California. Data collected by this project also continues to facilitate complementary research related to the NSF funded SAFOD project. Borehole network data ***contributes to the National Earthquake Hazards Reduction Program (NEHRP)*** by facilitating research supported by NEHRP and complementary research by investigators from other nations, and by providing fundamental input for models of time-dependent earthquake forecasts, on spatial-temporal clustering of earthquakes, on triggering of events, and on the systematic variations of deep slip rate in active fault zones. Additionally, the real-time monitoring of fault-zone process provides one of the rare hopes for understanding and tracking the nucleation of potential damaging earthquakes, an outcome, if eventually realized, that would aid significantly in reducing losses from earthquakes.

FINAL TECHNICAL REPORT:

HIGH-RESOLUTION MONITORING AT PARKFIELD

Introduction

As part of the U.S. Geological Survey initiative known as the Parkfield Prediction Experiment (PPE) (Bakun and Lindh, 1985), the operation of the High Resolution Seismic Network (HRSN) at Parkfield, California, and the collection and analysis of its recordings began in 1987. Figure 1 shows the location of the network, its relationship to the San Andreas Fault, sites of significance to previous and ongoing research using the HRSN, relocated earthquake locations, and the epicenter of the 1966 and 2004 M6 earthquakes that motivated the PPE. The HRSN records exceptionally high-quality data, owing to its 13 closely spaced three-component borehole sensors, its continuous recording of very wide band-width high frequency recordings (0-100 Hz), and its sensitivity to low amplitude seismic signals (recording events below magnitude -1.0) due to the extremely low attenuation and background noise levels at the 100-300 m sensor depths (Karageorgi et al., 1992). These data are also made readily available to the scientific community over the internet through the Northern California Earthquake Data Center (NCEDC). Several aspects of the Parkfield region make it ideal for the study of small earthquakes and their relation to tectonic processes. These include the fact that the network spans the transition from locked to creeping behavior on the San Andreas fault, much of the rupture zone of the repeating magnitude 6 earthquakes and NSF's San Andreas Fault Observatory at Depth (SAFOD) experiment. The area also has available three-dimensional P and S velocity models, a well-defined and simple fault segment, a homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right-lateral strike-slip), and is a region of non-volcanic tremor activity.

The HRSN project addresses the seismic potential hazard presented by large earthquakes on the San Andreas Fault system with high-resolution borehole recordings of low amplitude seismic signals in a region where several moderate to large earthquakes have occurred. It provides general information on earthquake source properties, on the detailed structure of the San Andreas fault, on the spatio-temporal distribution of deep fault slip, and on fault roughness and strength. It also directly contributes to NSF's EarthScope initiative "SAFOD" and to the development of time-dependent earthquake forecast models by providing earthquake recurrence data. The observational data and scientific inferences from data obtained from this project have been catalytic in spawning wide-ranging analyses and arguments over the fine-scale processes underway on seismogenic fault zones. On going studies at Parkfield using these data demonstrate conclusively the existence of an extremely regular and localized process of ongoing earthquake-accommodated slip in the fault zone. The unique data and consequential findings have significant implications for earthquake source dynamics, for earthquake forecasting, and for scaling relations among earthquake source parameters. Compelling evidence also exists for changes with time both in seismicity and in wave propagation that appear to be coupled. Sequences of near-identically repeating small earthquakes in the area are also providing a new method for monitoring the changing deformational strain field at seismogenic depth. Data and research results from this network also provide fundamental input to models of earthquake forecasting, on spatial-temporal clustering of earthquakes, on triggering of events, and on the systematic variations of slip rate on an active fault. This information is critical to earthquake risk estimation. The real-time monitoring of these fault-zone processes provides one of the rare hopes for understanding and tracking the nucleation of potential damaging earthquakes, an outcome, if eventually realized, that would be do much in reducing losses from earthquakes. Over time, the major investment operating and maintaining the data collection for the borehole network has produced a unique baseline of fault-zone behavior with distinct features observed rather than theorized, a body of observations that must be incorporated in new models for fault-zone deformation. Sustained operation of the 13 borehole station HRSN borehole network under grant 05HQGR0080 is helping to characterize seismic behavior in the target region of the SAFOD fault-zone drilling project. We are continuing to execute a basic program of operation, maintenance and archival of the network and network data under this grant and to continue our research program using the data to study the spatio-temporal details of microearthquake dynamics, wave propagation, slip-rate variations and nonvolcanic tremor activity.

Scientific Significance. The goal of the HRSN project has always been to acquire data to improve our understanding of fault zone dynamics at very high resolution (meters) and to develop precise characterization methods that will allow monitoring of the subtle changes in process and properties underway within a seismogenic fault zone capable of producing large earthquakes. Data and research results from this network have over the years provided and are continuing to provide fundamental input to models of earthquake recurrence, fault zone structure, strength and heterogeneity, spatial-temporal clustering of earthquakes, event triggering, earthquake scaling, fault zone and earthquake physics, and slip rate and strain accumulation on an active faults (information critical to earthquake risk estimation and loss mitigation). Throughout its 20 year history, the Parkfield High-Resolution Seismic Net (HRSN) has acquired unique data that are forcing a new look at several conventional concepts and models for earthquake occurrence and mechanisms, and has provided a baseline and characterization of seismic activity complete down to very low magnitudes that has proven critical to many previous and ongoing studies (e.g. the SAFOD component of EarthScope). The networks recording of very low amplitude seismic signals has also been instrumental in the recent discovery of non-volcanic tremor activity on the San Andreas Faults system (Nadeau and Dolenc, 2004).

The research began with NEHRP in 1986 as a proposed direct test with proven and modern technology of two hypotheses critical to our understanding of the physics of the earthquake process, implications for earthquake hazard reduction, and the possibilities for short-term earthquake prediction - major goals of the NEHRP:

1) That the earthquake nucleation process produces stress-driven perturbations in physical properties of the rocks in the incipient focal region that are measurable, and

2) That the nucleation process involves progressive and systematic failure that should be observable in the ultralow-magnitude microseismicity with high-resolution locations and source mechanisms.

Little did we know then about the power of borehole networks, where remarkably low noise levels opened a window on the realm of non-volcanic tremor activity and microearthquake observations at M<0 and frequencies to 100 Hz. This unprecedented resolution has driven our research (and that of many colleagues) for the past two decades, with many exciting discoveries. In a series of journal articles and Ph. D. theses, we have presented the cumulative, often unexpected, results of this effort. They trace the evolution of a new and exciting picture of the San Andreas Fault zone responding to its plate-boundary loading, and they are forcing new thinking on the physics and structure of earthquake faults in general and on dynamic processes and conditions within the fault zone at seismogenic depths and much deeper through observations of non-volcanic tremor.

Analyses of the Parkfield monitoring data have revealed significant and unambiguous departures from stationarity both in the seismicity characteristics and in wave propagation details. Within the 1966 M6 nucleation zone we have found a high Vp/Vs anomaly at depth (Michelini and McEvilly, 1991) (i.e., where the three M4.7-5.0 sequences occurred in 1992-94 and, more recently, where an anomalously high Q region in the fault zone appears through tomographic analysis to be the source volume where the fault-zone guided waves (FZGW) are generated (Korneev et al., 2003)). Synchronous changes well above noise levels have been seen among several independent parameters, including seismicity rates, average focal depth, S-wave coda velocities, characteristic sequence recurrence intervals, fault creep and water levels in monitoring wells (Karageorgi et al., 1997). We have been able to localize the S-coda travel-time changes to the shallow part of the fault zone and demonstrate with numerical modeling the likely role of fluids in the phenomenon (Korneev et al., 2000). This zone is also the upper part of the FZGW generation volume. We can connect the changes in seismicity to slip-rate variations evident in other (strain, water level) monitored phenomena.

New and unconventional scaling laws have also been developed from the Parkfield earthquakes that can be projected to fit earthquakes up to M7.4 diverse tectonic environments (Nadeau and Johnson, 1998; Igarashi et al., 2003; Chen et al, 2007) and to fossil earthquakes (pseudotachylite structures) of magnitudes as small as -2Mw (Wenk et al., 2000). These laws predict unprecedented high stress drops and melting on the fault surface for the smallest events, which is consistent with the melting observed from the exhumed pseudotachylites. Such results are highly unconventional and have spawned numerous investigations aimed at resolving the apparent inconsistencies with established paradigms of fault and earthquake behavior. Data from SAFOD could play a key role in resolving these issues and is being closely evaluated as it becomes available.

The more general significance of the project is its production of a truly unique continuous baseline, at very high resolution, of both the microearthquake and non-volcanic tremor pathologies and the subtle changes in fault-zone environment at depth. These data are openly available to researchers on the NCEDC archive, and provide the seismological community an earthquake laboratory available nowhere else. This unique body of observations and analyses has also provided much of the impetus for Parkfield as the preferred site for deep drilling into an active seismogenic fault zone (SAFOD). The network has recently completed a total hardware upgrade to modern real-time telemetry and data flow into the BDSN stream, and, with NSF support, the addition of three new borehole stations to better focus on the SAFOD drilling target. With the upgrade, expansion and other enhancements, the detection threshold of the HRSN in the SAFOD zone is now less than $-1.3M_l$, providing a complete baseline of very low magnitude microseismicity to aid in the operational and research objectives of SAFOD.

Reducing losses from Earthquakes in the U.S. A better understanding of earthquake physics, earthquake recurrence models, and fault zone processes are critical to reducing losses from earthquakes in the U.S., and our research is arguably fundamental to those goals. Results obtained from this data collection and research effort provide unique information on the strain accumulation on faults at depth, estimation of the strength and strength heterogeneity of earthquake generating faults (i.e. fault roughness), and on scaling properties of earthquake recurrence times and rupture parameters, all of which are critical input for accurate earthquake forecasts, fault rupture models, and ground motion and earthquake hazard estimation. Uniquely, through the study of characteristically repeating small earthquakes this work also promises to provide direct tests of earthquake forecast models by making predictions based on these models and assessing their success rates on time scales of months to a few years as opposed to decades to centuries as required for similar tests using large magnitude events.

Recent Activities

During the grant period, activities associated with the operation of the HRSN primarily involved six components: 1) routine operations and maintenance of the network, 2) major refurbishment of the network's solar power system to rectify lagging performance due to aging, 3) collaborative effort with the USGS and others to reduce costs and enhance data collection associated with the SAFOD experiment and to analyze HRSN, NCSN and SAFOD's temporary PASO deployments for refining the structure and target location estimates for SAFOD drilling, 4) The development of an automated pattern-scanning based approach to: a) increase the detection sensitivity and resolution of seismicity in support of SAFOD efforts, b) overcome diminishing resources due to flat funding and rising operations and maintenance costs, and c) process the dramatically increased number of events resulting from the aftershock sequence of the 2004 Parkfield M6 mainshock,

Operations and Maintenance: In addition to the routine maintenance tasks required to keep the HRSN in operation, various refinements and adjustments to the networks infrastructure and operational parameters have been needed this year to enhance the HRSN's performance and to correct for pathologies that continue to manifest themselves in the recently upgraded and expanded system. A feature of the new system that has been particularly useful both for routine maintenance and for pathology identification has been the internet connectivity of the central site processing computer and the station data loggers with the computer network at BSL. Through this connection, select data channels and on-site warning messages from the central site processor are sent directly to BSL for evaluation by project personnel. If, upon these evaluations, more detailed information on the HRSN's performance is required, additional information can also be remotely accessed from the central site processing computer at Parkfield. Analysis of this remotely acquired information has been extremely useful for trouble shooting by allowing field personnel to schedule and plan the details of maintenance visits to Parkfield. The connectivity also allows certain data acquisition parameters to be modified remotely when needed, and commands can be sent to the central site computer and data loggers to modify or restart processes when necessary.

The network connectivity also allows remote monitoring of the background noise levels being recorded by the HRSN stations. For example shown in Figure 2 are power spectral density (PSD) plots of background noise for vertical components of the 12 of 13 HRSN (JCSB was off-line during the event used for this PSD analysis). The PSD analysis gives a rapid assessment of the HRSN seismometer responses across their wide band-width. By routinely generating these plots with data telemetered from Parkfield, changes in the seismometer responses, often indicating problems with the acquisition system, can be easily identified, and corrective measures can then be planned and executed on a relatively short time frame.

Smaller scale maintenance issues addressed this year include cleaning and replacement of corroded electrical connections, grounding adjustments, cleaning of solar panels, re-seating, resodering and replacement of faulty pre-amp circuit cards, and the testing and replacement of failing batteries. Larger efforts related to major refurbishment of the solar power system are discussed in the next section.

Refurbishment of Power System: Detection, monitoring, and high-resolution recording of low-amplitude seismic signals (e.g., nonvolcanic tremors and earthquakes down to the smallest possible magnitude) with the highest possible signal-to-noise (especially in the region of SAFOD drilling) are major objectives of the HRSN data collection effort. The minimization of data loss due to station outages and data-dropouts is also critical to these objectives.

Over the previous several years, we have had a serious decline in the robustness of the power system components (primarily the aging solar panels and batteries that have been in use since initiation of the network in 1987) of the network. Simultaneous outages at multiple stations are now becoming an all too frequent occurrence and are seriously affecting efforts to monitor tremor and micro- and repeating earthquake activity in the Parkfield area.

For example, during the winter months, monitoring for nonvolcanic tremor activity using a standard detection set of 8 HRSN channels shows significant (and sometimes catastrophic) gaps in the data. Figure 3 illustrates the seriousness of the problem with an example from tremor monitoring during periods of overcast weather. During the 7 day period shown, all 8 stations used for monitoring tremor activity were out simultaneously for over 50\% of the time. The remaining 50% of the time, outages occurred for at least some of these 8 stations, resulting in significantly degraded capability for unambiguous detection of the low-amplitude tremor activity.

Further investigation, both remotely and on site, showed that these gaps occurred due to insufficient battery re-charge at many of the network's stations, which are remote solar powered installations. In previous years, similar but less severe data gaps have occurred during the winter months and have been attributed to overcast skies during the rainy season. In the winter of 2004 exceptionally heavy rainy season exacerbated the outage problem to an intolerable level, and to avoid a potential repeat of the situation, efforts are being undertaken to refurbish and upgrade the solar power systems. Specifically, the following steps are being taken:

1) replacement of the oldest batteries and switching of the remaining old batteries to the less power consuming pre-amplifiers;

2) improvement of the wiring scheme along the lines suggested by the solar power representative;

3) upgrade/replacement of solar panels. (Solar panels degrade at ~ 1% per year, and newer versions have improved output. Since the installation of the HRSN over 17 years ago, the same size/format panel has gone from 40 watts to 55). This is a relatively easy field task, and should gain us 20-30% capacity at each site.

Among the three newer sites (CCRB, SCYB, LCCB), both the batteries and solar panels are relatively new. Nonetheless, stations CCRB and LCCB both had some outages last winter, which is most likely explained by the limited sunlight in these areas due to hilly terrain. We have, therefore, added one more solar panel at each of these sites to enhance their power system robustness.

The table shown in Figure 4 summarizes the tasks of the power system upgrade effort, and shows the state of completion of the tasks as of early 2005.

Collaborative efforts with USGS and others: An intensive and ongoing effort by the EarthScope component called SAFOD is underway to drill through, sample and monitor the active San Andreas Fault at seismogenic depths and in very close proximity (within a few 10's of km or less) of a repeating magnitude 2 earthquake site. The HRSN data plays a key role in these efforts by providing low noise and high sensitivity seismic waveforms from active and passive sources, and by providing a backbone of earthquake and tremor detection and continuous waveform data from the numerous microearthquakes and tremors that are occurring in the general vicinity of SAFOD.

At this stage SAFOD drilling efforts are focused on obtaining estimates of the targets relative location to the existing hole to accuracies of meters if possible. This high degree of accuracy is required in order to target accurately three multi-lateral side cores for sampling and monitoring within the final target zone

HRSN Activities this year have contributed in two principal ways to these and longer-term SAFOD monitoring efforts as well as to reduce operational costs for the HRSN in general:

1) In collaboration with the USGS, we have integrated the 7 vertical HRSN channels telemetered from Parkfield into the NCSN triggering scheme (described above) to increase the sensitivity of NCSN detection in the SAFOD area. This has effectively doubled the number of small events the target location working group has for constraining the relative location of the target sequences.

2) Again in collaboration with the USGS, we have begun implementing a telemetry upgrade that will eventually allow all 38 channels of the HRSN data (both 20 sps and 250 sps data streams) to flow directly from Parkfield, through the USGS Menlo Park processing center, and also to the BSL for near-real-time processing and archiving on the web based NCEDC. This will provide near immediate access of the HRSN data to the community without the week's to month's delay associated with having to transport DLT tapes to Berkeley, upload, and quality check the data.

3) We have also applied our prototype similar event automated catalog approach to the primary and two secondary SAFOD target zones and were able to provide the SAFOD event location working group with rapid and precise double-difference and relative magnitude catalogs of 82 similar events in the zone immediately surrounding target region occurring between August 2001 and February 2005.

Figure 5 shows the double difference locations and estimated rupture dimensions (based on Nadeau and Johnson, 1998) of 67 of these events that were derived using one event from the SAFOD primary target sequence as the reference. Other primary target events are shown in green, and events from a secondary target located ~ 40 m to the southeast are shown in blue. Several other suspected repeating sequences can be seen as tight clusters of similarly sized events. We are in the process of confirming these events as characteristically repeating sequences members.

The SAFOD similar event catalogs are now being used by the working group to extract data from the corresponding PASO array, Pilot Hole, NCSN and mainhole data sets for integration with the HRSN data to provide as much and as detailed information as possible in the final push at locating the target sequence for the lateral side core drilling.

Automated Pattern Scanning: Circumstances relating to the dramatic increase in HRSN event detections spawned by the 2003 San Simeon and 2004 Parkfield earthquakes and by SAFOD drilling activity have required new thinking on how to catalog microearthquakes detected by the HRSN. One action taken to help address this problem has been to integrate HRSN data streams into the NCSN event detection and automated cataloging process (described above).

This approach has been successful at discriminating small events in the local Parkfield area from other types of event detections and for providing automated locations of a significantly increased number of small events in the local area (approx. double that of the NCSN network alone). However, the rate of local events from the HRSN sensitized NCSN catalog is still only catching about 1/2 the number of local events previously cataloged by the HRSN, and waveforms for the small events are not typically made available. In addition, unlike the previous HRSN catalog, the additional events added by the NCSN-HRSN integration are not reviewed by an analyst nor do they generally have magnitude determinations associated with them. In some cases, the selection rules used for the integrated catalog also result in exclusion of events that are otherwise included by the NCSN.

These limitations severely hamper efforts relying on similar and characteristically repeating microearthquakes. They also reduce the effectiveness of research relying on numerous very small magnitude events in the SAFOD zone (e.g. for targeting the SAFOD targets).

To help overcome these limitations, we have embarked on an effort to develop an automated similar event cataloging scheme based on cross-correlation and pattern scanning of the continuous HRSN data now being archived. The method uses a small number of reference events whose waveforms, picks, locations, and magnitudes have been accurately determined, and it automatically detects, picks, locates and determines magnitudes for events similar to the reference event to the level of accuracy and precision that only relative event analysis can bring.

The similar event detection is also remarkably insensitive to the magnitude of the reference event used, allowing similar events ranging over several magnitude units to be fully cataloged using a single reference event. It also does a remarkably good job even when seismic energy from multiple events is superposed. Once a cluster of similar events has been cataloged, it is a relatively straight forward process to identify characteristically repeating microearthquake sequences within the cluster (frequently a single similar event "cluster" will contain several sequences of repeating events).

Application of the method using one of the SAFOD target events as a reference is illustrated in Figure 5. The magnitude of the reference event is ~ 2.1. This event was scanned through 4.5 years of continuous data, and 67 other events occurring within a zone of ~ 150 m were detected (including 3 very small quakes that were not even detected by the HRSN REDI-type system). The magnitudes of these events ranged down to magnitude -1.2 Ml. In addition to the SAFOD target sequence from which the reference was derived, several other repeating sequences within the 150m zone were also identified (5 of which had not previously been known to exist).

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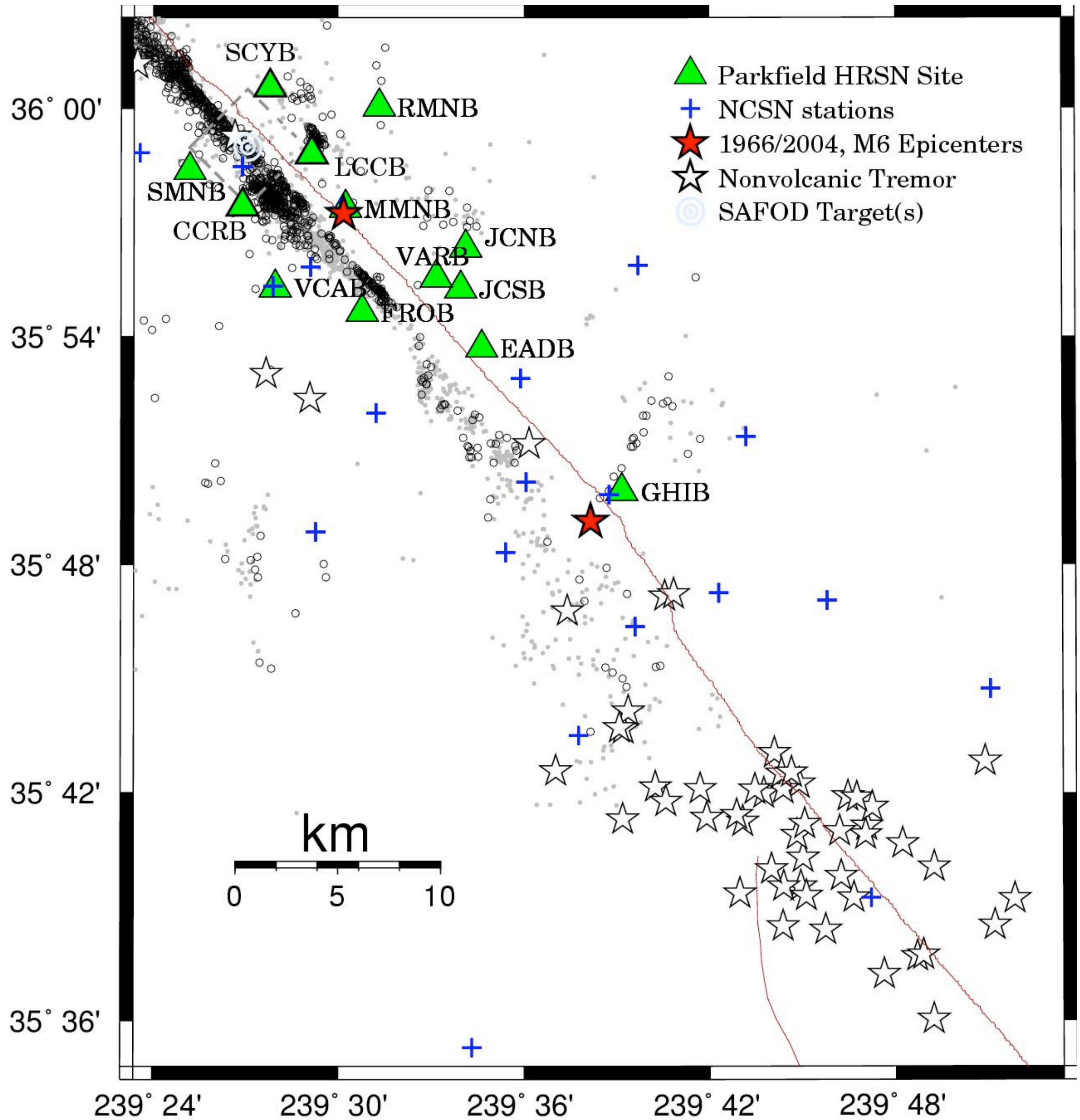

Figure 1. Map showing the San Andreas Fault trace and locations of the 13 Parkfield HRSN stations, the repeating M2 SAFOD targets (a 4 km by 4 km dashed box surrounds the SAFOD zone), and the epicenters of the 1966 and 2004 M6 Parkfield main shocks. Also shown are locations of the recently discovered nonvolcanic tremors, routine locations of earthquakes recorded by the expanded and upgraded 13 station HRSN (small open circles) and locations of events recorded by the earlier vintage 10 station HRSN relocated using an advanced 3-D double-differencing algorithm (gray points) applied to a cubic splines interpolated 3-D velocity model (Michelini and McEvilly, 1991).

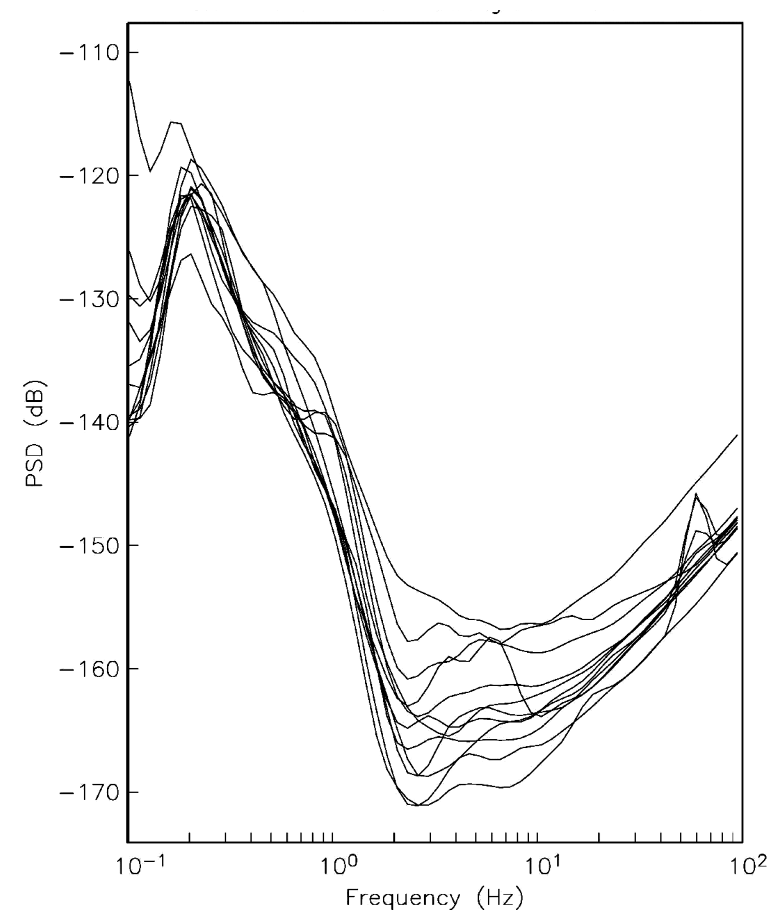

Figure 2. Typical background noise PSD for the 250 sps vertical component channels of the HRSN borehole stations as a function of frequency. The data are from 2 AM Local time on Sunday morning. Note the relatively low PSD levels and the overall consistency for all the HRSN stations. The 2 Hz minimum for the sensors occurs because of the 2 Hz sensors used at these sites. Below 2 Hz, noise levels rise rapidly and the peak at 3 sec (.3 Hz) is characteristic of teleseismic noise observed throughout California. EADB, GHIB and SCYB have a 60 Hz noise peak in the PSD, which is indicative of a ground loop problem. The PSD (dB) ranking of the stations of the stations at 2.9 Hz (near minimum PSD for most of the stations) is:

SCYB.BP.DP1 -171.05231
LCCB.BP.DP1 -170.58481
MMNB.BP.DP1 -168.70798
JCNB.BP.DP1 -167.85416
EADB.BP.DP1 -165.73283
SMNB.BP.DP1 -164.71182
FROB.BP.DP1 -163.79599
CCRB.BP.DP1 -163.56433
GHIB.BP.DP1 -161.44427
VCAB.BP.DP1 -159.84996
RMNB.BP.DP1 -156.86127
VARB.BP.DP1 -154.02579

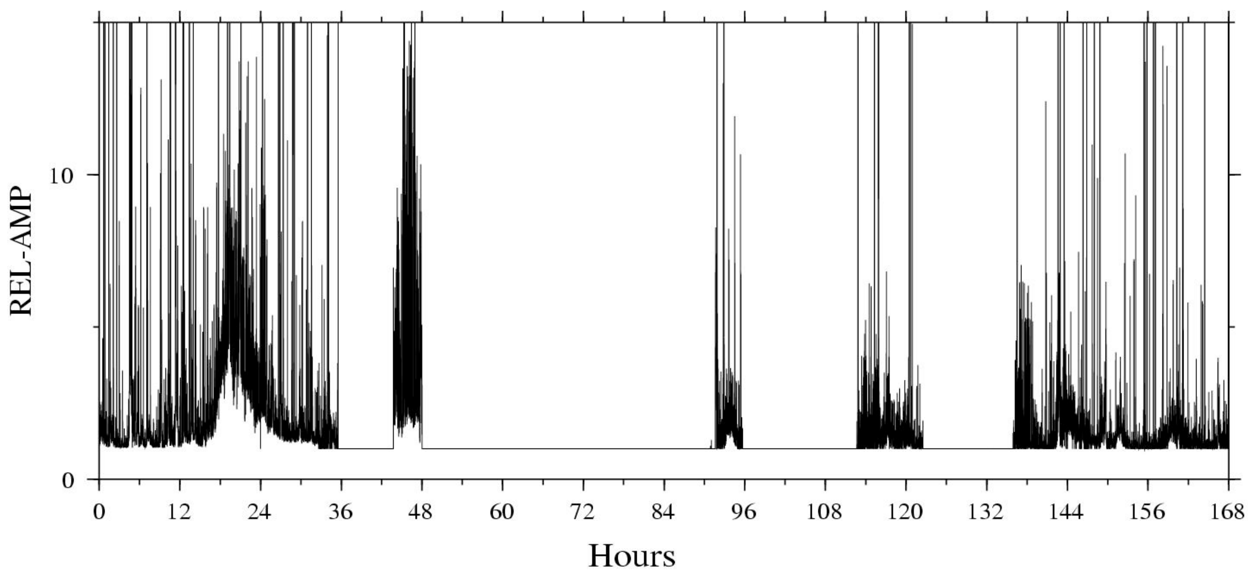

Figure 3 (above). Stacked root-mean-square seismograms for the 8 stations of the HRSN used in monitoring tremor activity. Shown are 7 days of data starting at Hour 00 (UTC) of day 7 of 2005. Times when relative RMS amplitudes (REL-AMP) are 1.0 indicate periods when all 8 stations were out simultaneously.

Figure 4 (below). Table of power upgrade tasks undertaken since mid-2004. Red indicates tasks yet to be completed as of early 2005. Tasks completed so far have removed the data drop outs and gaps that had plagued the corresponding network stations during the winter months.

HRSN POWER UPGRADES

Fall, 2005

Site	Data Logger Batteries (3/site)			Preamp Battery (1/site)		Data Logger Controller		Data Logger Solar Panels		Preamp Solar Panel		Q730 Serial Port		Site
	Age	Action	Rewiring	Age	Action	Type	Action	Status	Action	Status	Action	TD Output	Action	
JCSB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	All model M63**	REPLACE w/ old	M63**	REPLACE	4.6V	repaired	*JCSB*
RMNB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	5 M75 panels	good	M75	none	?	Repair	*RMNB*
VCAB	Recent	keep	done	Recent	keep	Flexcharge	replaced	Needs more panel	replaced w/ bigger	M40	replaced	4.2V	Repair	*VCAB*
SMNB	OLD	replaced w/ new	done	OLD	replaced w/ used	Flexcharge	replaced	Needs more panel	replaced w/ bigger	SM50-H	none	6.1V	Marginal	*SMNB*
CCRB	4-YR OLD	replaced w/ new	done	4-yr old	keep	Flexcharge	replaced	Needs more panel	replaced w/ bigger	two 10-watt	none	7.9V	good	*CCRB*
JCNB	Recent	keep	done	OLD	replaced w/ used	Prostar	good	Needs more panel	replaced w/ bigger	good	none	4.2V	repaired	*JCNB*
GHIB	OLD	replaced w/ new	done	"New Jan '99"	replaced w/ used	Prostar	good	1 M40, 3 M75	M40 replaced w/ M75	M40	replaced	failed	repaired	*GHIB*
MMNB	OLD	replaced w/ new	done	OLD	replaced w/ used	Flexcharge	replaced	5 M75 panels	good	M75	none	1.1V	repaired	*MMNB*
VARB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	4 M65**	replaced w/ 4 M75s	M65**	replaced	3.4V	repaired	*VARB*
EADB	OLD	replaced w/ new	done	OLD	replaced w/ used	Prostar	good	1 M55, 3 M75	M55 replaced w/ M75	M40	replaced	4.4V	repaired	*EADB*
FROB	Recent	keep	done	OLD	replaced w/ used	Prostar	good	1 model M40	done	M75 (2)	none	failed	repaired	*FROB*
LCCB	4-YR OLD	replaced w/ new	done	4-yr old	keep	Flexcharge	replaced	5 SM50-H	good	SM50-H	none	3.2V***	good (?)	*LCCB*
SCYB	4-YR OLD	replaced w/ new	done	4-yr old	keep	Flexcharge	replaced	5 SM50-H	good	SM50-H	none	7.6V	good	*SCYB*
GAS PK	4-YR OLD	replaced w/ new	done	NA	none	2 Prostar-30s	good	12 SP75	none	NA	none	NA	NA	*GAS PK*

NOTES:

*Replace (very) old preamp batteries with 4-yr-old batteries removed from Gastro Peak.

**Lower-voltage panels, intended to be used without a controller, 30 cells instead of the 33 cells on the 50-watt panels. Also very old.

***Capacitors are correct, yet voltage level is low. (??)

red =	To do	Jobs Remaining:	1 site replace solar panels	Panel inventory at Base: 1 M75, 4 SM50-H
orange =	Maybe do (2nd priority)		3 sites repair/test serial port	
green =	Done			

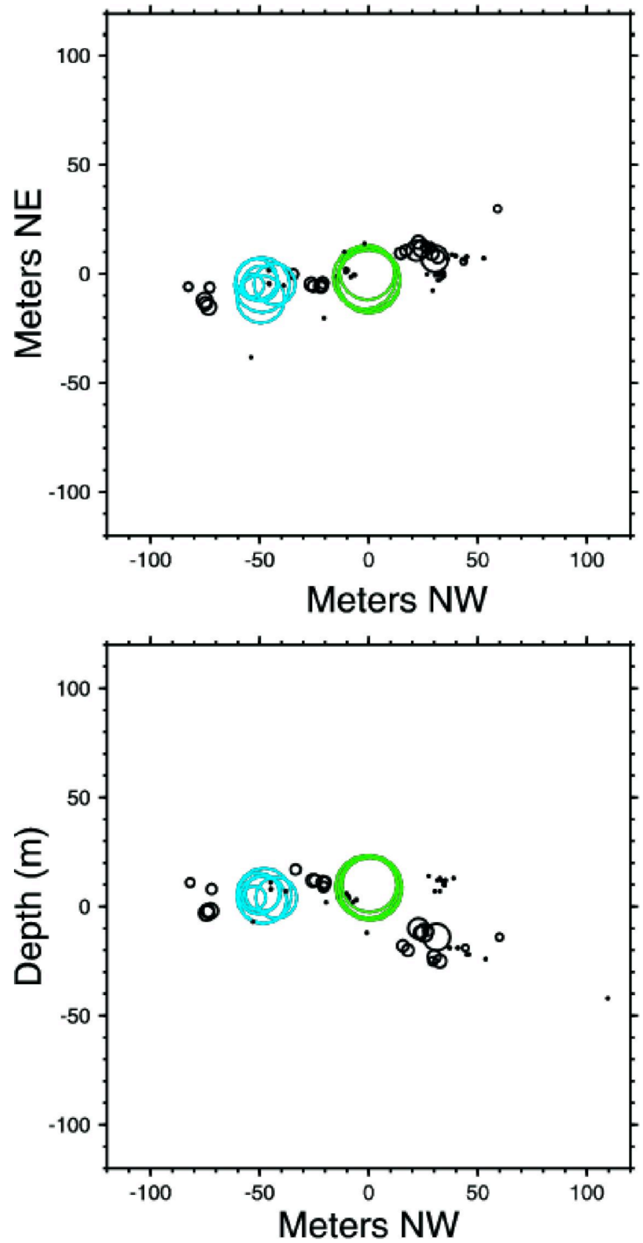

Figure 5. Map (top) and along fault depth section (bottom) views of double-difference locations resulting from application of the similar event pattern scanning and automated cataloging method using one of the SAFOD target events (green circles) as a reference. The magnitude of the reference event is ~ 2.1. This event was scanned through 4.5 years of continuous data, and 67 other events occurring within a zone of ~ 150 m were detected (including 3 v. small quakes that were not even by the HRSN detection scheme). The magnitudes of the 67 events ranged from 2.1 down to -1.2 Ml. In addition to the SAFOD target sequence from which the reference was derived, several other repeating sequences within the 150m zone were also identified (5 of which had not previously been known to exist).